BOUC-WEN MODEL PARAMETER IDENTIFICATION FOR A NEW MAGNETO-RHEOLOGICAL FLUID DAMPER USING PARTICLE SWARM OPTIMIZATION

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ABSTRACT

In constructing a reliable semi-active suspension system, the modelling of the damper is imperative as it produces the controllability on the suspension system. The modelling of Magneto-rheological (MR) fluid damper for the control device has been major focuses throughout the decades as semi-active systems are deems to be efficient in vibration suppression for various applications. MR fluid damper is abided by the behaviour of hysteresis model that not just predict the subsequent impact, but has the ability to retract the motion by the model internal memory. Acquiring a suitable model comes a setback from the natural existence of non-linearity from the MR fluid damper as the parameters of the hysteresis model may requires tuning as the response time for the absorber to response are in milliseconds. Hence, Particle Swarm Optimization (PSO) was introduced for altering significant parameters for Bouc-Wen hysteresis model to replicate the MR fluid damper performance in real-time. The objectives are succinct in three main criteria starting with the development of MR fluid damper, then a representation of hysteresis model and lastly optimizing these parameters by inducing PSO algorithm. Validations by physical experiment and simulation were conducted to enhance the justification of the present model. These performances are measured in force against displacement and force against displacement for the hysteresis model to depict MR fluid damper behaviour. The average marginal error was presented to strengthen the model along with analysis and discussion in deliberating the outcome. Approximation of the model demonstrates dependable fitting compared to the experimental data with the average marginal error ranging from 6.0 % to 8.3 %. The findings suggest that several parameters of the hysteresis systems requires boundary and by imposing the known sensitive variables to the model can emulated into near perfect model.

ABSTRAK

Dalam pembinaan sebuah sistem pergantungan separa-aktif, pembikinan struktur terhadap penyerap adalah penting untuk menghasilkan sistem pergantungan yang boleh dikawal. Untuk membikin struktur peredam cecair MR sebagai bahan kawalan telah menjadi tumpuan utama sejak kebelakangan dekad apabila sistem separa-aktif ini dikatakan berfungsi secara telus dalam mengagihkan gegaran bagi aplikasi yang meluas. peredam cecair MR ini mengandungi tingkah laku yang diperoleh dari struktur histeresis yang bukan sahaja boleh mengagak impak di masa hadapan, malah mempunyai kebolehan untuk menjejak kembali pergerakkan dengan kehadiran imbasan dalaman. Memenuhi sebuah modal yang sesuai, datangnya kekurangan dari lumrah azali pengkadaran yang tidak melurus dari peredam cecair MR di mana parameter-parameter histeresis modal mugkin memerlukan penalaan pada tindak balas masa yang berlaku dalam masa yang singkat milisaat. Jadi, Pengoptimuman Kawan Partikel (PSO) digunakan untuk mengubah parameter-parameter yang terbabit bagi struktur histeresis bagi menghasilkan struktur peredam cecair MR dalam waktu semasa. Objektif-objektif utama terbahagi kepada tiga bermula dari penghasilan peredam cecair MR, penyerupaan struktur hysteresis dan akhir sekali mengoptimumkan parameter-parameter dengan mengunakan algoritma PSO. Bukti dari eksperimen secara fizikal dan simulasi di jalankan untuk memperkukuhkan bukti penggunaan stuktur yang dilancarkan. Prestasi ini diukur melalui daya melawan kelajuan dan daya melawan ralat kedudukan. Purata beza dibentangkan bagi memperkuatkan analisa serta perbincangan atas hasil yang dikeluarkan. Anggaran dari struktur ini menunjukkan kebergantungannya terhadap eksperimen di dalam lingkungan 6.0 % ke 8.3 % purata perbezaan. Penemuan berasaskan atas dasar parameter-parameter daripada hysteresis memerlukan lingkungan dan dengan menyeterai pemalar yang sensitif untuk menghasilkan modal yang telus.

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ΔP	Pressure drop
ΔP_n	Viscous component
ΔP_τ	Field dependent induced yield stress component
Q	Pressure driven of MR fluid flow
L	Length
g	Fluid gap
w	Width of Annular Orifice
η	Plastic Viscosity of MR Fluid
$\boldsymbol{\tau_y}$	Field Dependant Yield Stress
C	Ratio of $\Delta P_\tau/\Delta P_n$
F_{shear}	Force Generated by Two Poles Plates
F_η	Viscous Shear Force
F_τ	Magnetic Field Dependant Shear Force
A	Pole Plate Area
S_{shear}	Relative Velocity between Pole Plates
V	Volume of Activated MR Fluid
λ	Desired Control Ratio
W_m	Mechanical Power Dissipation
S	Displacement of the Valve
H	Magnetic Field
l	Length of The Wire
N	Number of Coil Turn

i	Current Supplied to the Coil
μ	Relative Permeability of the Material
μ_0	Free Space Permeability
B_c	Magnetic Strength For The Core
B_w	Magnetic Strength At The Wall
ϕ	Magnetic Flux
B_g	Magnetic Strength At Fluid Gap
A_g	Cross Sectional Areas of the Fluid Gap
A_c	Cross Sectional Areas of the Core
A_w	Cross Sectional Areas of the Cylinder Wall
t_g	Fluid Gap
l_c	Core Length
l_w	Wall Length
c	Viscous coefficient
k	Stiffness Coefficient
α	Scaling factor of hysteresis
z	Hysteresis Displacement
β	Hysteresis Parameter
γ	Hysteresis Parameter
δ	Hysteresis Parameter
m	Mass
$u(t)$	Displacement
$F(t)$	Restoring Force
$f(t)$	Excitation Force
F_y	Yield Force

u_y	Yield Displacement
$z(t)$	Dimensionless Hysteretic Parameter
$sgn(\bullet)$	Signum Function
n	Exponential Parameter
k_e	Initial Stiffness
k_p	Post-Yielding Stiffness
f	Damping Force
f_0	Damper Force Offset
$\tau_{y(field)}$	Yield Stress Induced by the Magnetic Field
$\dot{x}$	Nonzero Piston Velocities
f_c	The Magnitude of Hysteresis
pbest	Best Position
gbest	Best Global Value
lbest	Best link
x_k^i	Initial Swarm Particles of Positions
v_k^i	Initial Swarm Particles of Velocity
i^{th}	Number Of Particle
rand	Uniformly Distributed Random Variable
p_k^g	Best Global Value
vmax	Maximum Velocity
φ	Constant Acceleration
c_1	Constant Acceleration
c_2	Constant Acceleration
w	Inertia Weight
D1	Wire Hole inside The Hollow Shaft

$D2$	Internal Diameter of The Piston Ring
$D3$	Inner Diameter of Internal Piston
$D4$	Outer Diameter of Piston Ring
$D5$	Height of Magnetic Choke
G	Fluid Gap
W	Flange Thickness
A	Ampere
F_{exp}	Experimental Data
F_{sim}	Simulation Data

LIST OF ABBREVIATIONS

2D	Two dimensional
3D	Three dimensional
ANFIS	Adaptive Neuro Fuzzy Inference System
BW	Bouc-Wen
DAQ	Data Acquisition
DS	Design Space
EH	Electro-Hydraulic
ER	Electro-rheological
GA	Genetic Algorithm
LVDT	Linear Variable Differential Transformer
MR	Magneto-rheological
MTS	Material Testing System
PSO	Particle Swarm Optimization
RMSE	Root-mean-square error
SGA	Standard Genetic Algorithm

CHAPTER 1

INTRODUCTION

1.1 RESEARCH BACKGROUND

Semi-active suspension application throughout the decades has seen promising potential predominantly on the stability and robust nature for controlling exerted vibrations in automotive particularly. Hence, the role of influencing the vibration is obliged by the damper. Magneto-rheological (MR) fluid is alleged to be a smart material that able to alter its resistivity with pertinent operation. In despite of the adaptable condition designated for the MR fluid damper, the sophistication on modeling the behavior has been scrutinized ever since.

Orientation of iron particles inside the MR fluid is influenced by the strength of the magnetic field that is dignified from the amount of current induced. Hence the resistive force that constraint the flow of fluid through orifice inside the piston is competent to regulate viscosity for the entire MR fluid damper system. In spite of having the feature to manipulate the restrictive force, the development of MR fluid damper ought to be realized. In drafting the suitable MR fluid damper in synchronizing with parametric identification, several factors are required to perform the investigation in intention for modeling and parameter identification. These aspects include the dimension of damper, geometric structural and magnetic design.

Identification methods withal have endured the modeling of MR fluid damper as an alternative source in replicating its performance. Supplementary, the bearing of MR fluid damper possesses hysteresis model systems. It relies on the current state inclusively with prediction of the forthcoming situation. Various techniques were applied in order to realize onto a leading model. Methods that are frequently associated with modeling are categorized either parametric or non-parametric. The importance of prototyping is to formulate the groundwork for applying into control strategies before extending the execution for semi-active suspension. Nevertheless, the complexity of modeling the MR fluid damper is erratic knowing the fact that absorber has nonlinearity feature. Furthermore, the drawback of hysteresis model is the presence of dynamic halt during intermission of input and output. An explicit hysteresis system called Bouc-Wen model suggested by Kwok demonstrates substantial quality as a modeling method to match the behavior of MR fluid damper (Kwok et al., 2006). It was modified from initial models discovered by Bouc in 1971 and further enhanced by (Wen, 1976) up till now it is well recognized as Bouc-Wen model. Kwok et al. (2006) revised certain traits from Bouc-Wen to ensure the stability of the hysteresis and performances to depict the MR fluid damper were consented.

In furtherance of imitating the MR fluid damper, Particle Swarm Optimization (PSO) method was introduced to enhance the parameter search for identification. The concept of PSO is emulating the social behaviors of wildlife interaction primarily in a clustered movement for instance in a flock of birds or swarming ants. The collaboration between (Kennedy and Eberhart, 1995) had leaded a renowned optimization method and has been seen in diverse application ever since. Subsequent to the motion of these groups, it has similar analogy to acquire best parameter value, for instance a flock of birds finding source of food in randomize formation until the location is found by another bird hence the position is predicted as an optimized position. This analogy is then applied onto the hysteresis model to locate the finest possible value in imitating the MR fluid damper characteristics.

Parametric modeling have arisen several drawbacks during processing as the domain of control force range is larger than the passive absorber. Subsequently the development of MR fluid damper has subjective limitations especially on the properties of amending the viscosity which rely on the amount of applied magnetic field. Thus the accuracy of modeling the hysteresis model has become major dispute amidst existing identification approaches. In addition to emerging complications, PSO has to endeavor the assignments of recalculating the utmost suitable parameters values for curve fitting of MR fluid damper model. Under these circumstances, extensive researches are required to increase the performances of hysteresis model that represents MR fluid damper. This is by the agency of implementing PSO algorithm to optimize the parameters values subsequently enhancing hysteresis model in replicating the MR fluid damper.

The main purpose of this research is to implement PSO to optimize the parameter values of the Bouc-Wen hysteresis model proposed by Kwok et al. (2006) that depicts the behavior of MR fluid damper.

1.2 PROBLEM STATEMENT

To acquire data from MR fluid damper and to be manipulated for optimization, a number of interjections must be sorted out prior to finalizing the end results.

1) The foremost predicament would be raised from designing the modular MR fluid damper that can satisfy emulating the behavior for parametric identification. In specific would be the coil design correlates to viscosity changes for given current input.
2) Modeling the MR fluid damper in hysteresis structure may result in uncertainties and augmented noise.
3) Optimizing using PSO carries the setback of depicting the hysteresis models in which the PSO parameters need to consider tolerance result and account the hysteresis parameters that are adjustment sensitive.

1.3 RESEARCH OBJECTIVE

Based on the research motivation, raised several queries:

1) Determine the functional and practical MR fluid damper that qualifies to be tested and compared with simulation from the structural and magnetic design.

2) Suggest an algorithm of PSO that is able to optimize the parameter value for hysteresis model that represents the MR fluid damper behavior using Bouc-Wen hysteresis model.
3) Determine the receptive hysteresis parameters that alter the behavior of MR fluid damper.

In this research, three hypotheses have been reached which are:

1) The structural design of MR fluid damper has distinctive specifications as the relation of resistive force and magnetic field strength influenced by current input.
2) Parameter values of Bouc-Wen hysteresis model proposed by Kwok capable of being optimized by using the advocated PSO algorithm.
3) There will be several hysteresis parameters that delicate towards the MR fluid damper modeling which leads to fluctuating results

The objectives of research are realized as:

1) To compose a control algorithm that proficient in enhancing the best parameters value by integrating experimental and simulation study consequently reproducing a noteworthy model of MR fluid damper to be utilize as a model controller of semi-active suspension device.
2) To prove that several hysteresis parameters are certainly requires regulation to generate agreeable MR fluid damper model and by deducing these boundaries the replication of a more realistic hysteresis model are practicable.

1.4 RESEARCH SCOPE

To reach the objectives as mentioned, the research scope has been clarified:

1) This research only focuses on mono-tube damper that has one reservoir for the fluid to flow. The structural and magnetic design is solely on the magnetic choke, the area of fluid passing through the orifice.

2) An original equipment of shock absorber was employed to enclose the primary objective of designing the dimension at magnetic choke to generate a bounded force and permitted operating current. The data collected from MR fluid damper performance was classified under distinguished test condition.

3) The parameter identification method proposed only on the algebraic function. The comparison of models was done within this subject to validate the leading model and subsequently the main reason is to optimize an existing model.

4) PSO algorithm was employed to enhance the performance of hysteresis Bouc-Wen models. The findings of the hysteresis parameters were amplified to depict the experimental data of the MR fluid damper for various test condition. The algorithm is preset to a reduce uncertainties of parameter search and was employed only as a method of parameter enhancer.

1.5 RESEARCH METHODOLOGY

The research activities were done in four stages. Firstly, the reviews on the development of MR fluid damper, hysteresis model and parameter identification were done. It was done for the comprehension on the current technology expansion with respect to MR fluid damper modeling using parametric identification and the algorithm PSO.

Next is the structural and magnetic design modification on the original damper. The proposed MR fluid damper is based on the operating platform for collecting data by experiment. When the design was finalized, the data was collected in various test conditions and stored for impending modeling verification.

Third, parametric identification was imposed beforehand in replicating the behavior of MR fluid damper. The algebraic function from a number of hysteresis models was steered by comparing selected models, Bingham, Bouc-Wen and Bouc-Wen by Kwok. Simulation method was operated in investigating these models either by employing MATLAB or Simulink reliant from the model intricacy. Significant parameters that initiate the modeling of hysteresis model profile were identified. The assessment was preceded to PSO algorithm for optimizing the suitable model for reproducing the MR fluid damper performance. Optimization method was done via MATLAB code parallel to the hysteresis model acquired by parametric identification stage.

Lastly the verification of the simulation results with reference to the experimental data was attained by elementary statistics procedure. Parameters acquired from the enhanced hysteresis models are examined. The validation on the best fitting model is investigated through the marginal error and further justified by the percentage error on each point between retrieving records experimentally and the numerals results from simulation. For every test condition the outcome was observed and justification for the results was deliberated.

The flowchart of research activities is done by the following steps as in Figure 1.1

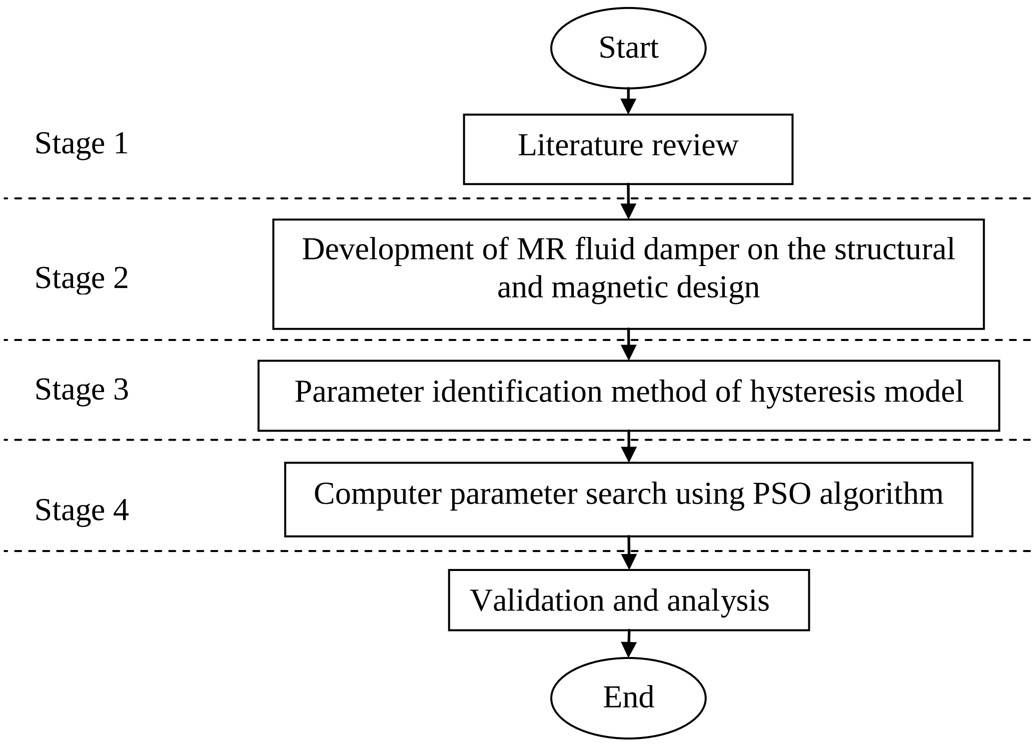

Figure 1.1: Flowchart of research activities

1.6 THESIS STRUCTURE

This thesis is structured as follows:

Chapter 2: Literature review – discussion on the MR fluid damper development, parametric hysteresis modeling, PSO algorithm in the perspective of background and research literature.

Chapter 3: Research methodology – the outline of research development is extracted into hardware and simulation phases from elaborating on the MR fluid damper design and collecting damper performances the simulation synthesizing and overall evaluation results can be achieved.

Chapter 4: Results and discussion – results obtained from previous chapter was deliberated for analysis apprehension. The prime hysteresis model was determined from hysteresis comparison, implementation of PSO has enhanced the model and optimized parameters were resolved. The justification was done by underlining the error between experimental and simulated results.

And lastly **Chapter 5: Conclusion –** conclusion of the entire experiment based on the construction of this research and proposed improvements for future research work.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

In this chapter, a review on the MR fluid damper design, hysteresis model comparison and PSO operation is discussed. The review follows the basis of this research according to practical realization of this project. Three main aspects on this review will sum up extending to the scope for generalizing the research project.

MR fluid damper is a type of controllable device which has the property to change its viscosity depending on the applied magnetic field. Hysteresis model depicts the behaviour of the damper correlates to the input/output relationship. Parametric model are based on mechanical principle including interpretation by arranging springs and dashpot. PSO)is an optimizing technique based on population and individual search finding from emulating social interaction (i.e. bird flocks) (Kennedy and Eberhart, 1995).

2.2 MR FLUID DAMPER

The MR fluid is defined as a smart material that can shift its property and early discovery was dated back in the 1940's (Rabinow, 1948; Winslow, 1947; Winslow, 1949). The manipulative system allows vibrations suppression ploughed on the performance in civil and mechanical structures. A survey was conducted where MR fluid damper as a semi-active devices, in which a property can be accustomed immediately but the system cannot receive energy (Dyke and Spencer, 1997). The versatility and adaptability of active systems are maintained by these device and act as dependant passive devices denote recognition for MR fluid damper to be unswerving.

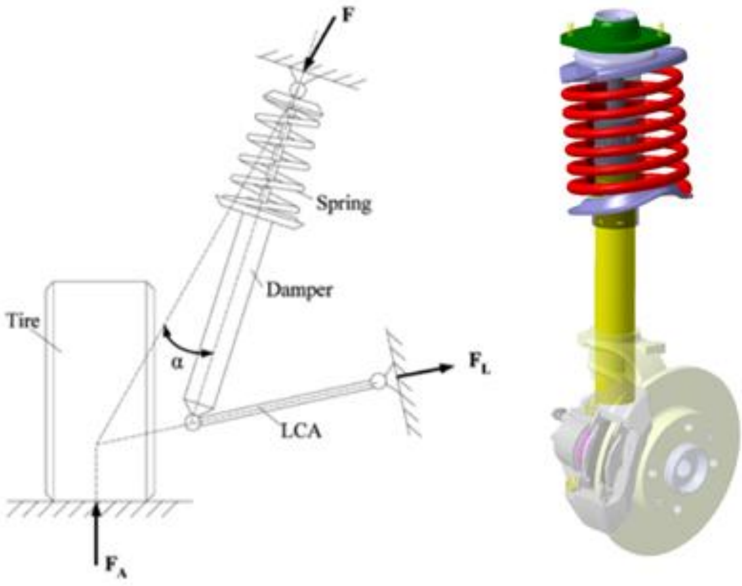

Figure 2.1: Suspension schematic

Source: Liu et al. (2006)

Figure 2.1 shows a representation of a suspension system. It consists of spring, damper, mountings, knuckle and linkage (arm). The stiffness of the system is carried by the spring which isolates the vehicle body from disturbances, thus energy is released and supply vibration to the system. This is where shock absorber dissipates the energy supplied. By applying the damping coefficient into the system equation, it equalise the vibration from releasing and dissipating energy.

The elastic element usually a coil spring carries the static load from the suspension system. It conveys forces proportional and opposed to the suspension elongation. The damping element however is the absorber or damper which differs from user's specification. Hydraulics shock absorber, electro-hydraulic (EH), magneto-rheological (MR) or electro-rheological (ER) often seen on applications and technologies of semi active suspensions. The reason is because dynamic behaviour of the system is controlled by these dampers to enhance the stability of the body and delivers negligible force at steady-state. The mechanical linkage element primarily links up the suspension system to the body in other words sprung body to the unsprung mass.

2.2.1 Damper advancement and classification

Recent technologies on suspension systems have expanded to a new approach that categorize each suspension technology on its significant characteristics (Hrovat, 1997; Guglielmo et al., 2008; Isermann, 2003). The first case of active suspension, it can be narrowed down to three well executed applications on the active field; load-levelling, slow-active and fully-active. The difference between all of these is the actuation framework of the bandwidth that the suspension can withstand. For load-levelling the bandwidth is at the fine underline of the main suspension dynamics, however bandwidth between body and wheel dynamics, and full-bandwidth is the slow-active and fully-active suspensions respectively.

There are two criterion to elaborate electronically controlled suspensions; energy input and bandwidth. The main comparison to notify the differences between active and semi-active is by energy insertion into the system. It is classified as 'Active' when energy is 'supplied' to the system, on the other hand it is considered as 'semi-active' when the suspension system is electronically customized to exclude energy insertion apart from the energy to steer the electronic parts. If the suspension can 'lift' the vehicle it said to be active or else it is semi-active systems.

Bandwidth is the other feature that characterizes the suspension system. It is the element in such that the specific reaction-time response can be modified electronically. Figure 2.2 represents the classification between passive, semi-active and fully active suspension systems (Ikhouane and Rodellar, 2007).